FlatSat Workshops Teaching Fundamental Electronics Skills for CubeSat Building

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Abstract

The University of Nottingham (UoN) recently established its own CubeSat programme, with the team commencing design, construction and testing of the first CubeSats in late 2020. However, one major challenge encountered was a common lack of practical applied electronics skills amongst students. This was repeatedly noted by students as a major obstacle to project success in progress reviews for WormSail, our first CubeSat project. Notably, these sorts of skills are also an area of common concern for young workers and employers in the UK Space Sector. This skill gap existed despite the student team coming from a variety of STEM (Science, Technology, Engineering and Math) undergraduate backgrounds, including physics, computer science, and aerospace and mechanical engineering. With insufficient time to recruit students with electronic engineering backgrounds, it proved difficult to find "all-rounders" to join the team with the broad range of skills required for the project.

One advantage that several students had however was their experience from informal hobbies involving Arduino and Raspberry Pi (RPi) based microcontroller electronics. These were found to endow highly transferrable skills, with these members providing significant contributions to the team through their skills and teaching. Team members found these so useful, that the "FlatSat" programme was set up to provide electronics teaching resources for new members of the CubeSat team. Sessions within the programme could be planned and delivered by the experienced team members, and hence be targeted to include applicable, referrable, and important skills and knowledge for building CubeSats.

Through developing these resources, the team realised it may be beneficial to include this programme in taught modules offered in the Faculty of Engineering, to enhance practical skills for all students enrolled in these modules.

This paper is intended to overview the work carried out in developing the FlatSat teaching workshop, and highlight the resources and their benefits to groups including other higher education space module conveners, developing CubeSat teams, School and further education teachers, STEM Outreach Coordinators, and general hobbyists. It is hoped that boosting confidence with such in-demand skills will be of great benefit to learners. We will also review case studies of the first large-scale workshop sessions and outline plans for future developments, particularly taking into consideration the feedback of demonstrators, students, and observers to the workshop.

Keywords

FlatSat, CubeSat, Electronics, Education, Outreach

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Introduction

In the Autumn-Winter of 2020, the University of Nottingham (UoN) commenced work on its first student CubeSat project, eventually named “WormSail” [1]. WormSail had a challenging delivery schedule of approximately 4 months, owing to a discounted short notice launch slot. This necessitated an accelerated and flexible approach to CubeSat development and in particular assembly, integration, testing and validation (AITV) activities. Consequently, the project was approached using the LeanSat design philosophy to varying degrees of success as discussed elsewhere [1].

One result of this was that the inexperienced student team had to rapidly acquire a variety of practical electronics skills for successfully integrating the commercial off-the-shelf (COTS) components of the CubeSat, along with developing custom student payloads from different components and circuits. Despite members of the team having had several years of university education in engineering, physics, or computer science (all regarded as heavily technical degrees which did include some electronics modules and labs), very few were confident enough to develop, test, and verify many electronics setups. As this initial project was ran mainly through Aerospace Engineering, it was difficult to involve students from Electronics Engineering at such short notice.

Self-admittedly, even simple methods and skills for laboratory electronics were either missing, half-remembered or based solely on theory; progress was further hindered by the high price tag of the components being worked on, which reduced the confidence of students to work with the electronics lest they be damaged. Some of the skills discussed as important but missing include:

- Use of benchtop power supplies to safely provide the correct voltage to components, without under- or over-limiting the current to them, such as re-charging Electrical Power System (EPS) batteries or deployment thermal cutters
- Understanding how to read pinouts and how they showed power and data connections over jumper pins and PC104 stacks
- The different common data transfer protocols in microelectronics (UART, I2C, SPI) and how these functioned with their pins and software. If something wasn’t a USB or phone cable – we were lost!
- How common grounds would function for power and data transfer applications, and that sometimes loads are required for proper and stable power circuits
- The differences in other pins on microelectronics including GPIO, digital and analogue – and how these relate to input and output logic voltage levels and power transfer
- How breadboards, jumpers, multimeters, and oscilloscopes could be used to fault-find in circuits.

As can be seen, even these relatively basic electronics skills have direct and beneficial applications to the building of real, flight-capable CubeSats. Notably, a lack of “Practical, hands-on electronics” training amongst job candidates is a key area of concern for young workers and employers the UK Space Sector, as highlighted by recent a survey commissioned by the UK Space Agency [2] and elsewhere [3].

A few of the team members, however, had limited experience working on extra-curricular projects and hobbies using microcontrollers such as Raspberry Pi’s (RPi’s) and Arduinos. Skills they had acquired from these hobby electronics were immensely transferable to CubeSat development and were quickly communicated and disseminated throughout the team. Following postponement of the launch date for WormSail, the team decided to utilise these experiences to develop a solution to the “skills shortage” within the CubeSat team. These would teach students many of the simple electronics skills listed above that were found to be lacking, in a way that would bridge the gap between electronics and IT theory they were familiar with and what is required for CubeSat development. Thus, the idea for developing our “FlatSat training kit” was born. Alongside inspiration from hobby electronics, the idea of the training kit was inspired by the use of so called ‘FlatSats’ which are used as high-fidelity engineering models for testing during actual CubeSat missions [4]. Ultimately, while the involvement of students with backgrounds in electronic engineering is desirable for university CubeSat development, we believe that the FlatSat training kit is also a valuable tool for education and outreach.

1. The General FlatSat Kit & Design

1.1. FlatSat Kit Overview

The general aims of what we wanted our kit to look like included:

- Fit within a small breadboard: ~ PocketQube or CubeSat sized
- Be buildable (and dis-assembled) without requiring any additional soldering by students. Using jumper wires would be ideal due to their ease of use and reusability
- At least show primary satellite functions: on-board computer (OBC) coding, battery power, sensors for science payloads, radio transceivers with data messages
- Programming through COTS micro-controllers (RPi, Arduino, Micro:bit, etc)
- Programmable/controllable from student laptops, with minimum installation required
- Be very expandable/modular - easy to add/remove new components or activities as required
- All components easily (and cheaply) available, can be "bulk" ordered
- Budget of ~£100 per kit, and need to make at least 8 kits
- Be capable of running an activity workshop with school/university students within 2 hours
- Would be centered around 4 main "teaching objectives" - electronics, coding, team working, and spacecraft systems engineering

These initial requirements drove the team to plan the kit around a miniature setup of breadboards COTS microcontroller boards, jumper cables and the other components.

Many of the commercially available CubeSat training or teaching products are of reduced benefit in situations such as these. Some are prohibitively expensive (of the order of several hundred or thousand dollars each) and/or are aimed at teaching such specific skillsets (Attitude Determination and Control System (ADCS), Telemetry, Tracking and Command (TT&C), etc.) that they "skip" steps in teaching basic electronics (understandably they assume some previous experience). Expensive kits, while able to offer excellent learning tools and experience with space technology, means limited numbers can be bought or used at once, physically limiting student opportunities for hands-on work (which students clearly value greatly as a rare opportunity with space technology) [2,3]. Others can be simplified and are more accessible, but also typically come with printed circuit boards (PCBs) fully assembled, and thus removing key opportunities for students to develop their electronics understanding such as wiring or data interface methods. These more accessible approaches are very useful for training students familiar with the systems (but for mostly testing software rather than building skills) but are either too simple to assemble or too complex to rapidly understand the precise processes occurring through the circuitry for shorter learning sessions. Even the scratch-built, open-source projects available online typically assume a competency with skills such as electronics and coding that is not particularly new-user-friendly, and has limited scope for advice given the designs' often unique characteristics. Furthermore, "real" CubeSat hardware (with flight potential) is very rarely as "plug and play" as advertised, and (paradoxically) usually requires some experience to setup, integrate, configure and test for the first-time use (even with instructions).The team envisioned FlatSat kits to be a simpler, more affordable, more "ground-up" solution to these products, and to ensure it was obvious to students that the pieces they were handling weren't specialty components that need an expert to select and integrate, but could be done easily by anyone once certain core principles are learned.

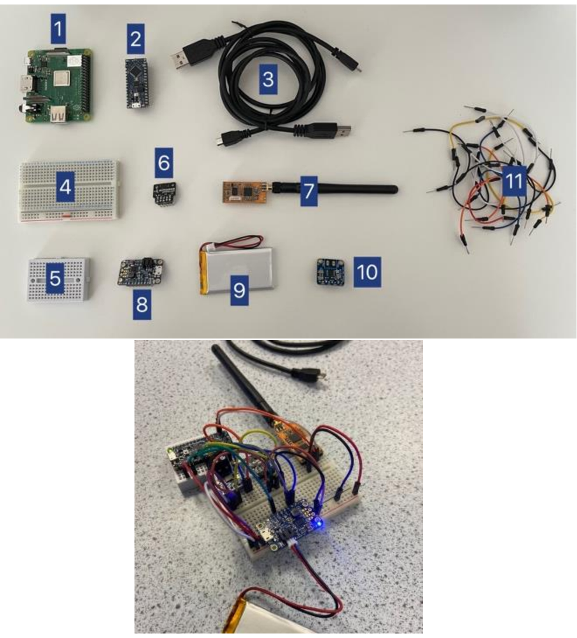


Figure 1: Top, all the components required for the basic kit, as provided to the students. Bottom, the fully assembled basic kit (~£100)

As seen in Figure 1, the basic initial kit would function using:

- An Arduino Nano Every microcontroller as the OBC controlling the individual subsystems.
- A radio transceiver using an APC220 – selected for its simple interface using UART pins; a “wireless serial port” as someone quipped.
- A power regulator board would enable flexible input options from Lithium-ion cells, solar panels or power banks; while also providing jumper outputs to match the rest of the kit (teaching power doesn’t always need to come through a USB cable with a connector).
- Sensors including an INA260 power meter that could be used to monitor current consumption by the kit (showing what needs 3V3 vs 5V too), or input from mini solar panels (providing EPS-functionality).
- Additionally mini “payload” sensors were used such as an inertial measurement unit (IMU) or environmental sensor for proof of the kit's utility and flexibility. Software for all these components was formed by modifying pre-existing open-source libraries online.

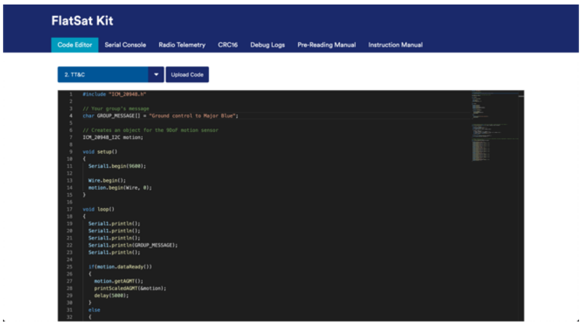
1.2. FlatSat Implementation in Workshops

After discussions with teaching staff at the University, we outlined some initial lesson plans to involve teaching small teams of 2-4 students per kit, how to assemble and test their kits while following written instructions in 1–2-hour sessions. These would initially be aimed at third- and fourth-year engineering undergraduates undertaking space modules, as well as training sessions for our extra-curricular CubeSat team, or fun outreach sessions such as enrichment activities at the university.

When developing the FlatSat kit, the team intended to bridge the skillsets from common sense computing and microelectronics, to CubeSat AITV, as closely as possible. This meant that a system such as Arduino microcontrollers was superbly suitable. Their one-program-at-a-time method of coding, compared to a system such as a RPi that has a full user-interfaced operating system (OS), provided an additional analogue to CubeSat OBCs. It is however advisable to carefully introduce this method of programming to students, as full graphical user interface (GUI)-based OSs (e.g. laptops, phones, etc.) will be more familiar to them.

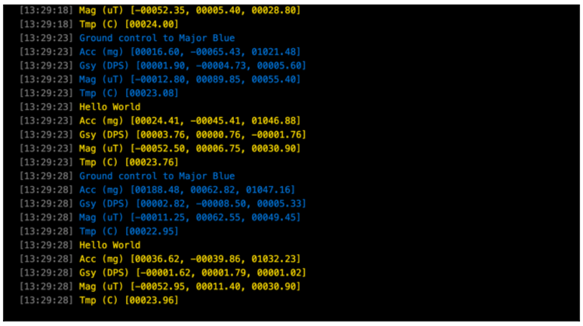
However, requiring students to pre-install and understand a selection of software and Arduino libraries before the workshop was deemed too complex for an introductory session. Instead, all the required software was bundled onto RPi 3A+ “programming stations” that were distributed alongside each kit. These were accessed in the sessions over a dedicated LAN website by selecting the appropriate MAC address of a team’s programming station from a list (we simplified this by having the RPis appear as pre-determined team colours on the list). Hence students would select the code they wanted to be uploaded to the Arduino from the list on the website (e.g. the beacon code to test the APC220 radio was wired correctly), and were able to flash this to the Arduino via the programming station, without requiring any additional software on their own device.

Students would come to the workshops with only their laptops, assemble the kits in teams and then plug them (via a RPi-based programming station) into their laptops and upload pre-written codes to them from our “homemade” LAN website, complete with accessible GUI (see Figure 2). Once complete, students could send radio messages from their kits (including text they wrote and data from the sensors) to a lab “ground station” (a RPi 4, with a APC220 receiver), which would print their messages (in their team colours!) to a projector screen at the front of the class (see Figure 3). The LAN website for code uploading was also hosted on this RPi 4, which enabled a centralised method for checking if any teams’ laptops or RPis were failing to connect to the LAN properly.



```
#include "ICM_20948.h"

// Your group's message
char GROUP_MESSAGE[] = "Ground control to Major Blue";

// Creates an object for the 9DoF motion sensor
ICM_20948_I2C motion;

void setup()
{
  Serial1.begin(9600);

  Wire.begin();
  motion.begin(Wire, 0);
}

void loop()
{
  Serial1.println();
  Serial1.println();
  Serial1.println();
  Serial1.println(GROUP_MESSAGE);
  Serial1.println();

  if(motion.dataReady())
  {
    motion.getAGMT();
    printScaledAGMT(&motion);
    delay(5000);
  }
  else
  {
```

Figure 2: The front-facing LAN website, for editing and uploading code to Arduinos



```
[13:29:18] Mag (uT) [-00052.35, 00005.40, 00028.80]
[13:29:18] Tmp (C) [00024.00]
[13:29:23] Ground control to Major Blue
[13:29:23] Acc (mg) [00016.60, -00065.43, 01021.48]
[13:29:23] Gsy (DPS) [00001.90, -00004.73, 00005.60]
[13:29:23] Mag (uT) [-00012.80, 00089.85, 00055.40]
[13:29:23] Tmp (C) [00023.08]
[13:29:23] Hello World
[13:29:23] Acc (mg) [00024.41, -00045.41, 01046.88]
[13:29:23] Gsy (DPS) [00003.76, 00000.76, -00001.76]
[13:29:23] Mag (uT) [-00052.50, 00006.75, 00030.90]
[13:29:23] Tmp (C) [00023.76]
[13:29:28] Ground control to Major Blue
[13:29:28] Acc (mg) [00188.48, 00062.82, 01047.16]
[13:29:28] Gsy (DPS) [00002.82, -00008.50, 00005.33]
[13:29:28] Mag (uT) [-00011.25, 00062.55, 00049.45]
[13:29:28] Tmp (C) [00022.95]
[13:29:28] Hello World
[13:29:28] Acc (mg) [00036.62, -00039.86, 01032.23]
[13:29:28] Gsy (DPS) [-00001.62, 00001.79, 00001.02]
[13:29:28] Mag (uT) [-00052.95, 00011.40, 00030.90]
[13:29:28] Tmp (C) [00023.96]
```

Figure 3: A screenshot from the ground station interface, showing two teams' data

2. FlatSat Workshop Activities

2.1. MMME3079 Test Workshops

Following test sessions with trusted members of the CubeSat team and staff, the first FlatSat workshops were first run as an optional workshop session available to third year engineering students taking the “Introduction to Space” (MMME3079) module. In these workshops, students received a short pre-reading manual explaining various useful terminology and principles (e.g. how breadboards function) to read before the workshop. They would then assemble the kits piece by piece (testing at various steps through uploading different pre-made codes) until it was the complete setup shown in Figure 1 above. Invitation to sign up for these workshops were also sent to members of the student Space Society, with some attendance. The total of estimated participants was 20-25 students.

Figure 4: Students working in small groups during the first workshop session in Nov 2021

2.2. Enrichment Week Workshops

As part of extra-curricular “enrichment week” activities ran by the Faculty of Engineering, students from any Department and year were encouraged to come along. Within the sign-up sheet going online, all 30 slots were filled within 3 days. These teams performed the same workshop activities as described in 3.1, although with revised instructions based on feedback from the first session.

2.3. MMME4038 Workshops & Lab Report

25% of the credits available for the “Spacecraft System and Design" (MMME4038) fourth-year module came from students’ grades in a laboratory report, to be filled with data acquired during in-person lab sessions. These sessions included three 1-hour FlatSat workshop sessions and two 1-hour sessions with the Theia Space ESAT simulator. As a masters-level module, the depth of learning required for these sessions would be greater than before, hence the team split each 1-hour session into subsystem dedicated subjects – EPS, TT&C, and Payloads.

1. The EPS session involved building the base kit (without the radio) but using solar panels as a power source. Students recorded power input/output values using the INA260 sensor by changing jumper positions in the circuit. They also tested solar panel performance at different inclinations and distances from light sources, using an angle-labelled turntable and mobile phone torches respectively.
2. The TT&C session added the APC220 radios to the setup, and required students to analyse a simple pre-coded beacon message using 16-bit cyclic redundancy checks (CRC16) to identify errors artificially introduced to the message using a random character replacement function. They also experimented with sending and receiving data commands to control an RGB programmable LED, and fix a purposefully hidden coding error using a method analogous to bus-injection.
3. The Payloads session used a combination of the previous environmental sensors to teach differences between UART, SPI, and I2C data lines. Students also got to examine samples in a “mystery box” using miniature cameras and spectrometers. They would then be asked to identify them based on data sent back – e.g. “what colour is the sample?”, “what part of Earth have you just imaged?”

The data students acquired in these workshops would be used to write up a module “lab report”, to review what they had learned from using the kits, and prove they could interpret their results and its relevance to real space missions.

Figure 5: Groups of students assembling their kits during the EPS session

3. Student Feedback

Informal feedback from students who have participated in these workshops highlighted how these sessions were able to offer a range of benefits, from helping with individual project theses, to solidifying the content taught in lectures via practical activities. One student mentioned how the skills learned through these workshops helped them during job applications, as they were able to show key skills which other applicants lacked. Several people also encouraged the team to adjusting the workshops to be more suitable for outreach and then utilise them for events in high schools, university open days or welcome week activities.

4. Conclusions

We present an open-source, affordable, and most importantly, accessible kit design for educational organisations to use and adapt for teaching students about technology. This includes electronics, coding, radio, and power systems; the fact we based ours around a CubeSat setup is just one vehicle for delivering these skills and learning outcomes. Similar setups with a few additional components could be used to teach about automobiles, drones, mobile phones or remote-controlled robots.

A further take-home message to aspiring CubeSat, or other space project, development teams is not to underestimate the number of blind spots and skill gaps you and your team will have. Any and all large-scale systems engineering projects require dedicated cooperation between disciplines and specialties, and so does the space sector. Assumptions that one's large theoretical knowledge of space systems and a capacity for learning new skills in world-record time is enough to carry your team through, is likely to lead to blockages, delays, and undue stress.

Future plans include simplifying the kit and its messages for use in school-level outreach; "de-mystifying" what is commonly thought of as technology levels beyond the understanding of most students in a class. Additionally, there are plans to enhance the fidelity of FlatSats towards a CubeSat or PocketQube sized system, including stackable subsystem boards with purpose made PCBs and headers. These extended activities should maintain good accessibility, but would enable differentiation to prioritise software or hardware focussed lessons. Following student feedback, the team will also include greater emphasis on interactive coding and increased emphasis on providing pinouts. Additionally, the team plans to incorporate LEDs into the design to help with easy fault finding, and the use of alternative programmers (such as Python-based RPi Picos) to reduce issues with software.

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References

[1] D. Robson, Y. Ferreira, H. Cope,, P.K. Da Cás, L. Cormier, G. Lionço, S. Thompson, R. da Silva, M. Ghelfi, A. Arcia Gil, The WormSail CubeSat: An International Educational Project To Elevate Space Science And Education, *72nd International Astronautical Congress,* Dubai, 2021

[2] Sant. R, P. Roe, E. Osborne, L. Hallam, and H. Sullivan-Drage, "Space Sector Skills Survey 2020," 2020.

[3] R. Garner and J. Dudley, "Removing Roadblocks from the UK space skills pipeline: A student and young professional perspective," *2nd Symp. Sp. Educ. Act*., 2018.

[4] S. Walsh et al., "Development of the EIRSAT-1 CubeSat through Functional Verification of the Engineering Qualification Model," *Aerospace*, vol. 8, no. 9, p. 254, Sep. 2021, doi: 10.3390/aerospace8090254.